

Particle Physics in 2002 :

State of the Field

Dieter Zeppenfeld

UW Madison

State of the SM

EW tests

Neutrino oscillations

B physics

Higgs search

New physics

Supersymmetry

Extra dimensions

Calculations at the Frontier

State of the Standard Model

90's saw dramatic confirmation
of the SM as the effective theory
of particle interactions

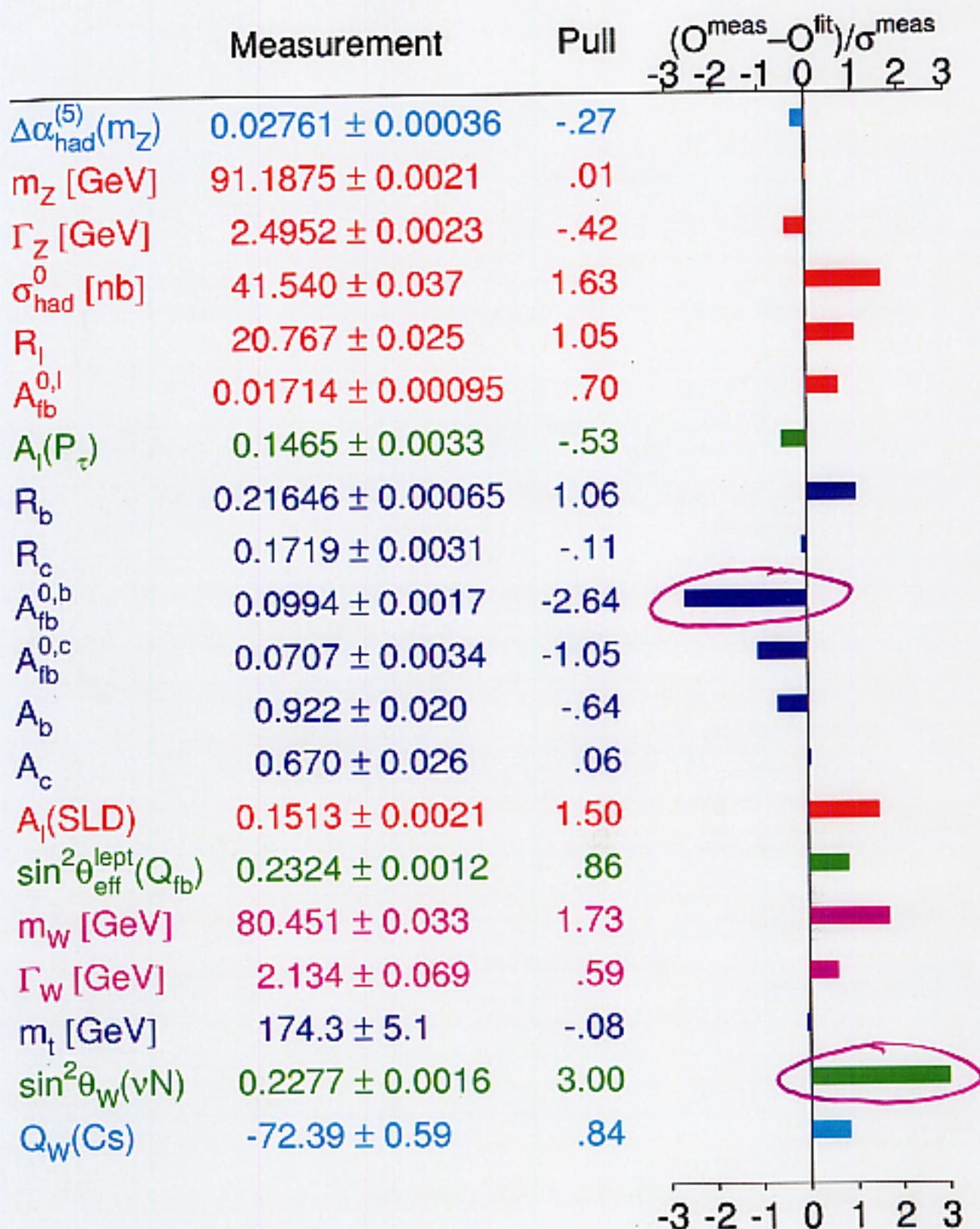
Discovery of top at Fermilab

$$m_t = 174.3 \pm 5.1 \text{ GeV}$$

Precision electroweak studies

- leptonic & hadronic rates at LEP
- FB and polarization asymmetries (LEP & SLC)
- W mass measurements (LEP & FNAL)
- atomic parity violation
- ...

Winter 2002



Should we worry? get excited?

Probability of χ^2 fit [Tully, DPF 2002]

all data: ~1.7 %.

without NuTeV: ~14 %.

⇒ reexamine systematic errors, in particular underlying theory model

For NuTeV

- NLO QCD corrections?
- isospin violations from QED effects?
- pdf assumptions ($s=\bar{s}$)?

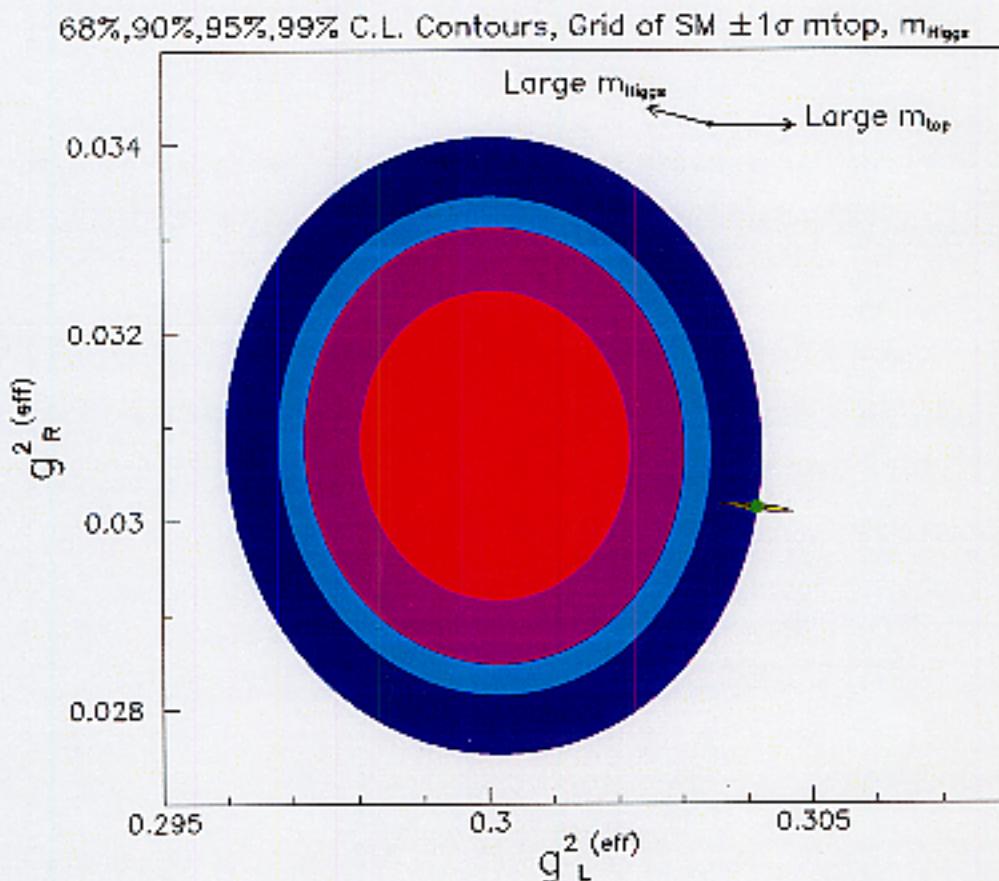
Quark Couplings: $(g_L^{\text{eff}})^2$ and $(g_R^{\text{eff}})^2$

2 parameter fit to $R_\text{exp}^\nu, R_\text{exp}^{\bar{\nu}} \Rightarrow (g_L^{\text{eff}})^2, (g_R^{\text{eff}})^2$

$$R^\nu = g_L^2 + r g_R^2 \quad g_L^2 \equiv u_L^2 + d_L^2$$

$$R^{\bar{\nu}} = g_L^2 + \frac{1}{r} g_R^2 \quad g_R^2 \equiv u_R^2 + d_R^2$$

Radiative corrections modify $g_{L,R}^2 \rightarrow (g_{L,R}^{\text{eff}})^2$



NuTeV measures:

$$(g_L^{\text{eff}})^2 = 0.3001 \pm 0.0014 \quad (\text{SM: } 0.3042)$$

$$(g_R^{\text{eff}})^2 = 0.0308 \pm 0.0011 \quad (\text{SM: } 0.0301)$$

$$\rho_{\text{corr}} = -0.02$$

- Assuming predicted ν coupling, $(g_L^{\text{eff}})^2$ appears low

New physics for NuTeV can be parameterized by $\nu\nu\bar{q}q$ 4-fermion interaction

$$\mathcal{L}_{4f} = \pm \frac{4\pi}{\Lambda_{LL}^2} \bar{\gamma}_\mu \gamma^\sigma \gamma_\mu \bar{q}_L \gamma_\sigma q_L$$

$$\text{e.g. } \Lambda_{LL} \sim m_{Z'} / \sqrt{2}$$

NuTeV result requires: $\Lambda_{LL} = 4.5 \pm 1 \text{ TeV}$

New physics must be $SU(2)_L \times U(1)$ invariant

$$\gamma_\mu \rightarrow L = \begin{pmatrix} \gamma_\mu \\ \mu^- \end{pmatrix}_L \quad q_L \rightarrow Q = \begin{pmatrix} u \\ d \end{pmatrix}_L$$

$$\mathcal{L}_{4f} = \pm \frac{4\pi}{\Lambda_1^2} \bar{L} \gamma^\sigma L \bar{Q} \gamma_\sigma Q \pm \frac{4\pi}{\Lambda_2^2} \bar{L} \gamma^\sigma \tilde{\gamma}_\sigma^2 L \cdot \bar{Q} \gamma_\sigma \tilde{\gamma}_\sigma^2 Q$$

\Rightarrow new physics in $\bar{\mu}_L \mu_L \bar{q}_L q_L$ interaction

Sizable "Cabibbo" mixing in quark and
lepton sector + absence of FCNC

- ⇒ Family universal contact interactions
are strongly preferred
- ⇒ expect $\bar{e}_L e_L \bar{q}_L q_L$ contact terms

Constraints from

HERA $e p \rightarrow e j X$

LEP $e^+ e^- \rightarrow q \bar{q}$

Tevatron $q \bar{q} \rightarrow e^+ e^-, \mu^+ \mu^-$ etc.

Result of global analysis

[K.Chenng, hep-ph/0106251]

$$\Lambda_{1,2}^\pm > 12 \dots 24 \text{ TeV} @ 95\% \text{ CL}$$

Other experiments should have seen
deviation also.

Impressive confirmation of the SM

$$\mathcal{L} = \mathcal{L}_{\text{matter}} + \mathcal{L}_{\text{gauge}} + \mathcal{L}_{\text{Yukawa}} + \mathcal{L}_{\text{Higgs}}$$

$$\mathcal{L}_{\text{matter}} = \sum_{\psi=L,e_R,\tau_R} \bar{\psi} i \not{D} \psi$$

$$D_\mu = \partial_\mu - ig_s T^a A_\mu^a - ig \frac{\vec{\tau}}{2} \cdot \vec{W}_\mu - ig' Y B_\mu$$

$\sim 10\%$ level for strong interactions

10^{-3} level for electroweak

$$\mathcal{L}_{\text{gauge}} = -\frac{1}{4} A_{\mu\nu}^a A^{a\mu\nu} - \frac{1}{4} \vec{W}_{\mu\nu} \cdot \vec{W}^{\mu\nu} - \frac{1}{4} B_{\mu\nu} B^\mu$$

few percent level for TGV:



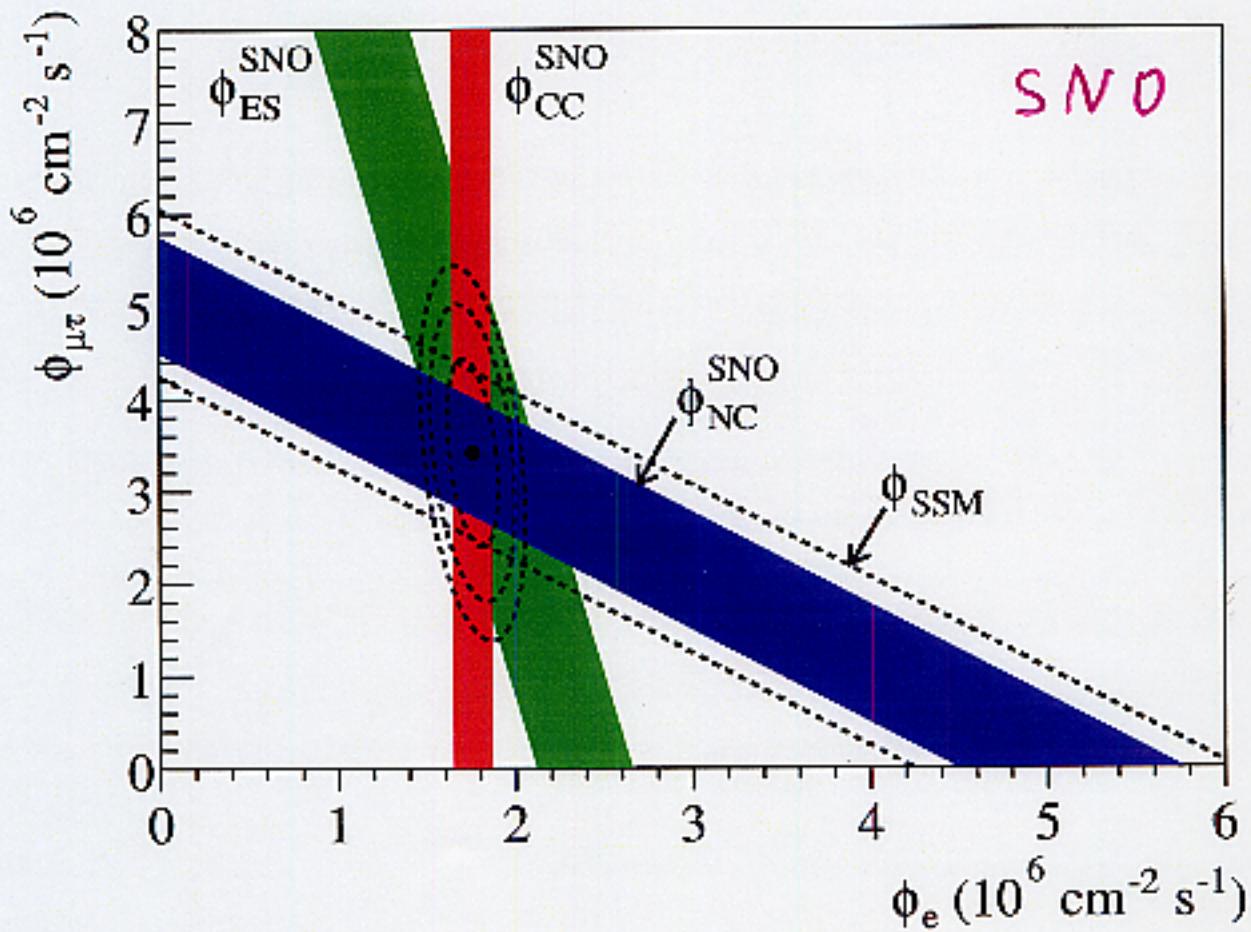
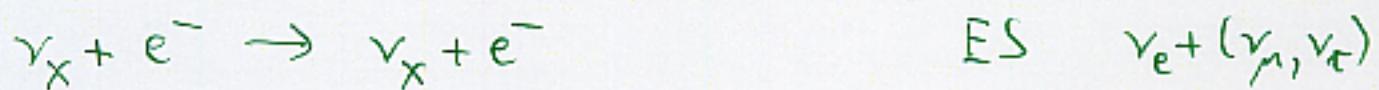
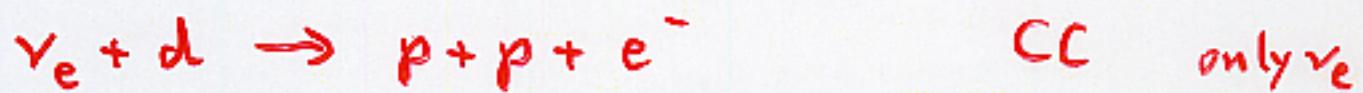
Yukawa and Higgs Lagrangian are crucial to explain masses. Do they embody the correct dynamics?

Neutrino oscillations

Experiments have revolutionized our understanding over past few years

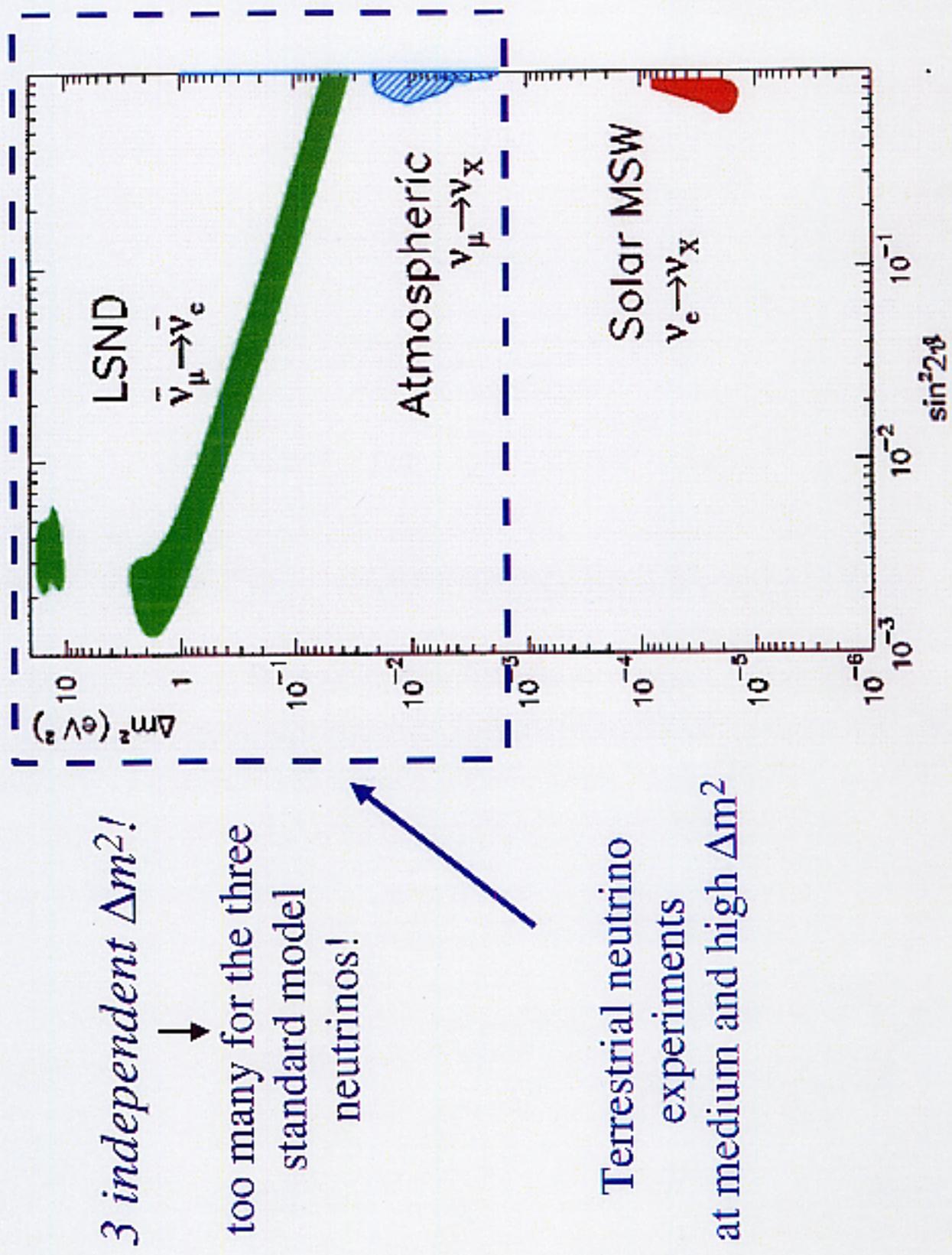
- Neutrinos have mass
- Flavor eigenstates vs mass eigenst show \approx maximal mixing
- Confirmation and resolution of the solar ν puzzle

Separate solar flux measurements

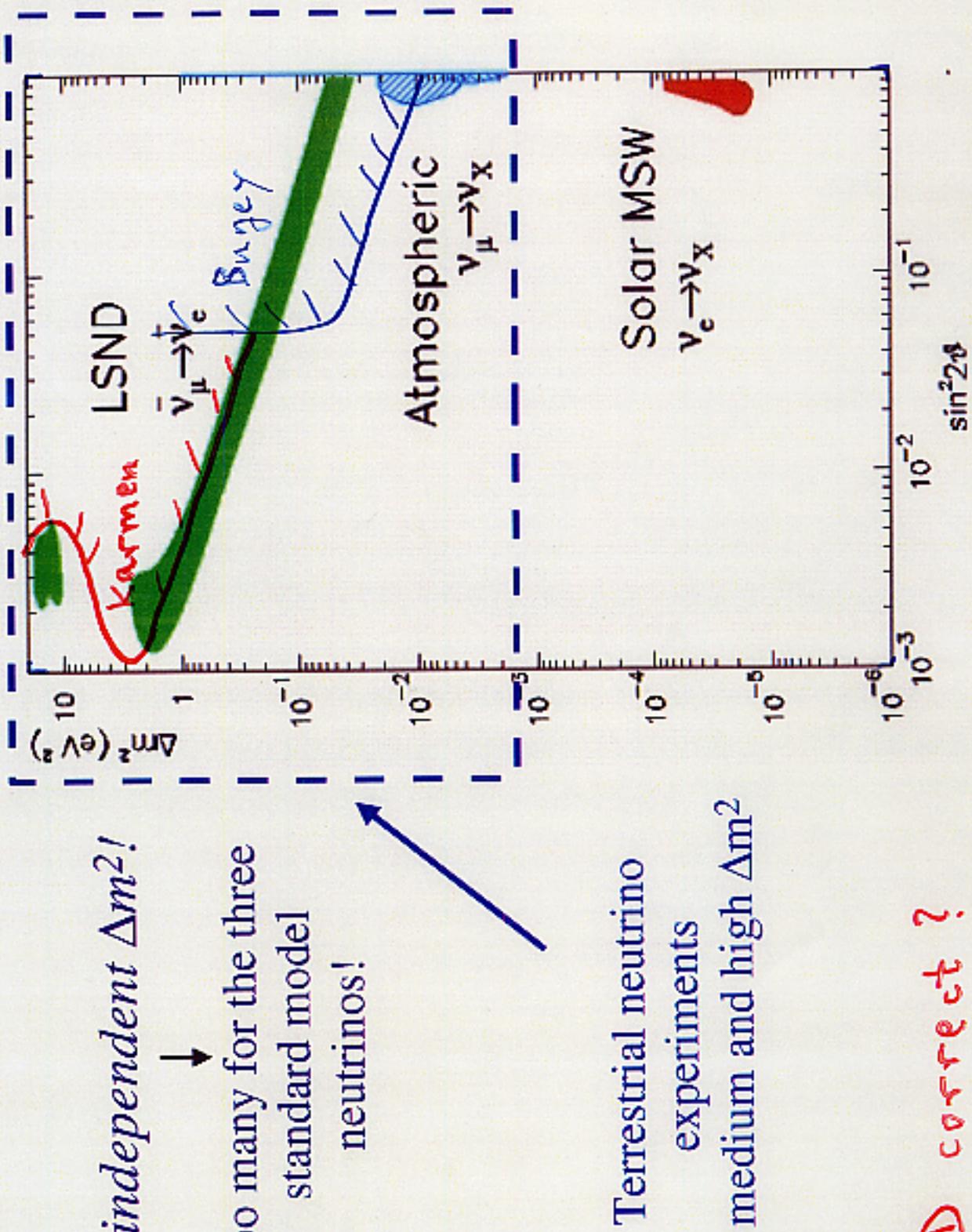


Overall $\phi_{\nu_e + \nu_\mu + \nu_\tau}$ as predicted by SSM
[Bahcall et al.]

Neutrino Oscillation Signals



Neutrino Oscillation Signals



is LSND correct?

Atmospheric & solar oscillations only

3 mass eigenstates

$$\begin{array}{c} m_3^2 \\ m_2^2 \\ m_1^2 \end{array} \quad \left. \begin{array}{l} \{ \delta m_{\text{atm}}^2 \\ \{ \delta m_{\text{sol}}^2 \end{array} \right.$$

Can be described by trivial extension of SN

$$L = \begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L \quad \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L \quad \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_L$$

$$e_R, \nu_R = e_R, \nu_{eR} \quad \mu_R, \nu_{\mu R} \quad \tau_R, \nu_{\tau R}$$

Higgs v.e.v., $\phi \rightarrow \begin{pmatrix} 0 \\ (v+H)/\sqrt{2} \end{pmatrix}$, produces masses and mixing

$$\mathcal{L}_{\text{Yukawa}} = \sum_{ij} \left[\Gamma_{ij}^{\nu} \bar{L}_i \phi^e \nu_{Rj} + \Gamma_{ij}^e \bar{L}_i \phi e_{Rj} + \text{c.c.} \right]$$

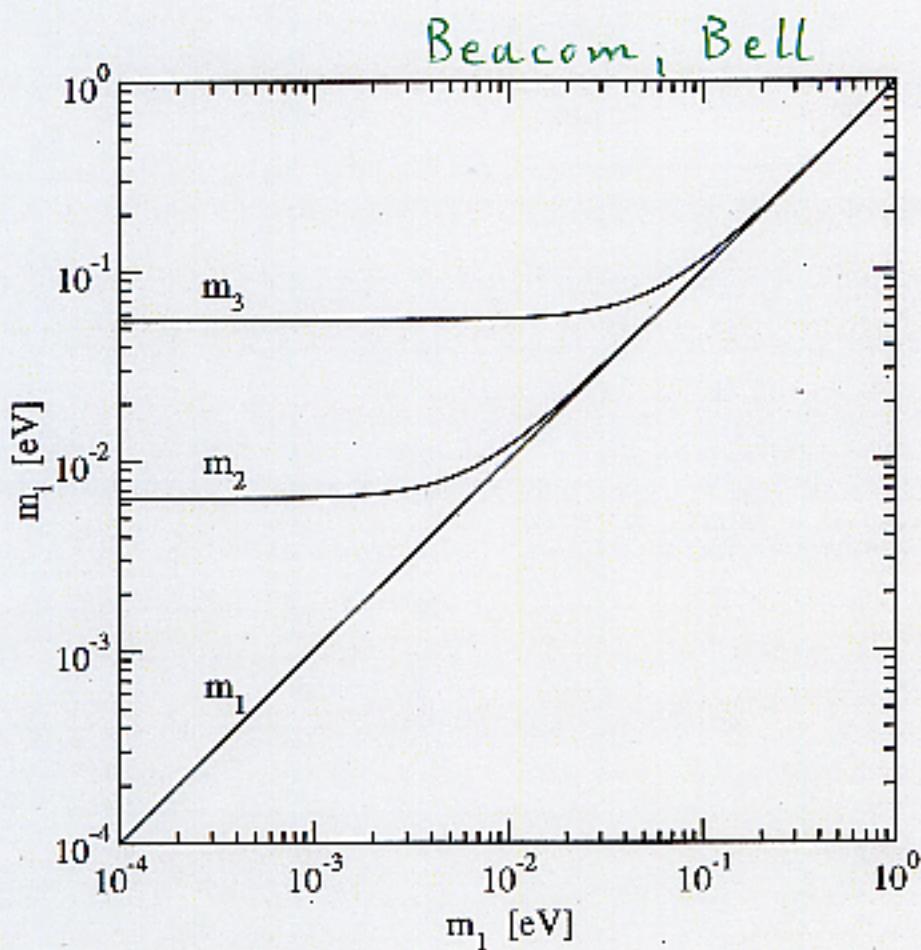
Why is $|\Gamma_{ij}^{\nu}| \sim \frac{mv}{v} \sim \mathcal{O}(10^{-12})$?

Why is $\frac{me}{v} = 2 \cdot 10^{-6}$?

Naive see-saw mechanism

$$m_{\nu_i L} = \frac{m_{i\ell}^2}{M}$$

does not fit observed δm^2
from oscillations



$$m_2^2 = m_1^2 + \delta m_{\text{sol}}^2$$

$$m_3^2 = m_2^2 + \delta m_{\text{atm}}^2$$

$$\frac{m_3}{m_2} \approx 10 \ll \frac{m_\tau^2}{m_\mu^2}$$

Need more data to probe new physics

LSND might be correct

$\nu_\mu \rightarrow \nu_e$ at MiniBooNE

Presence of sterile neutrinos

$\nu_\mu \rightarrow \nu_s$ vs. $\nu_\mu \rightarrow \nu_\tau$ at MINOS

Neutrinos have Majorana mass

Or $\beta\beta$ decay

We live in golden age for
neutrino physics!

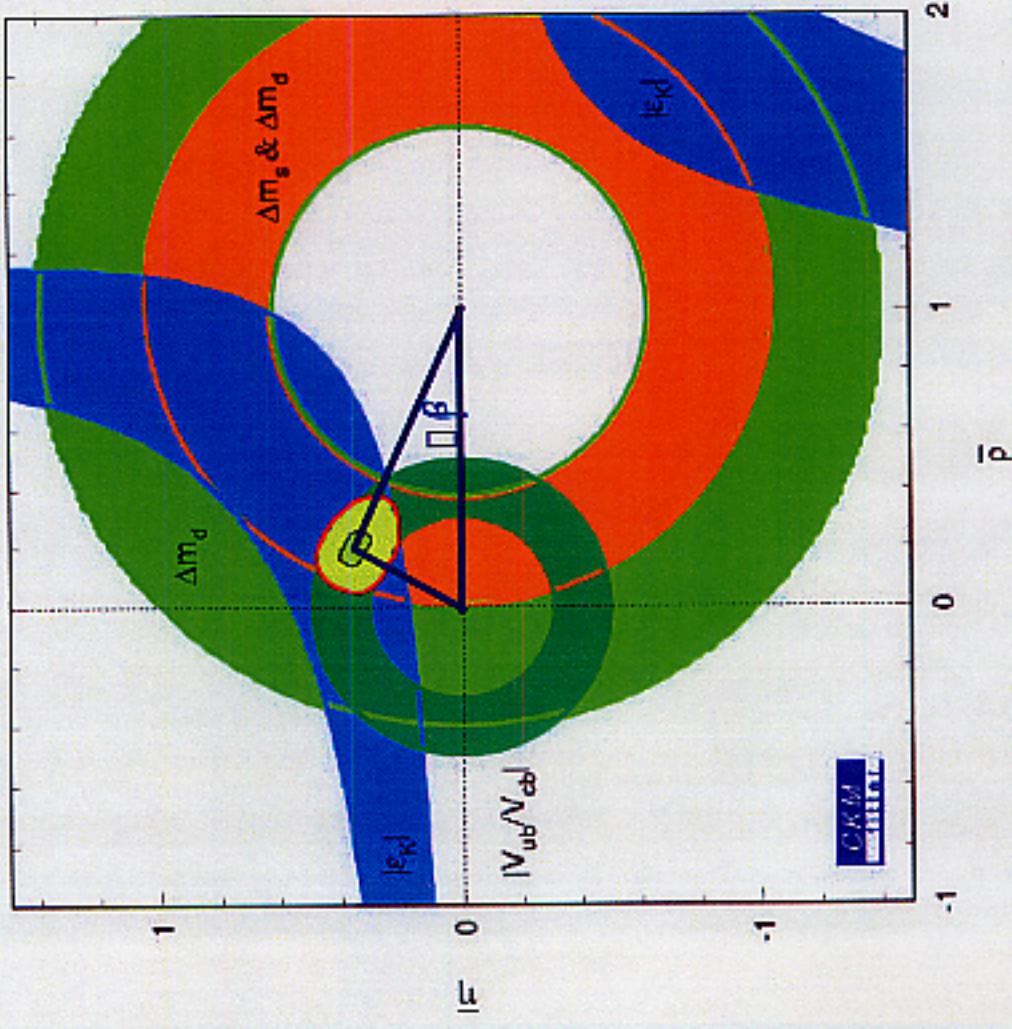
B Physics

Belle and Babar have each collected $\sim 90 \text{ fb}^{-1}$ of data

Scrutinize B system as never before

- CP violation
- CKM angles
- Rare decay modes ($b \rightarrow s\gamma$ etc.)
- Two body modes ($B \rightarrow \pi\pi$ etc.)
- QCD studies
- Input from lattice QCD
- ⋮

Constraints on upper vertex of Unitarity Triangle from all measurements EXCEPT $\sin^2 \beta$

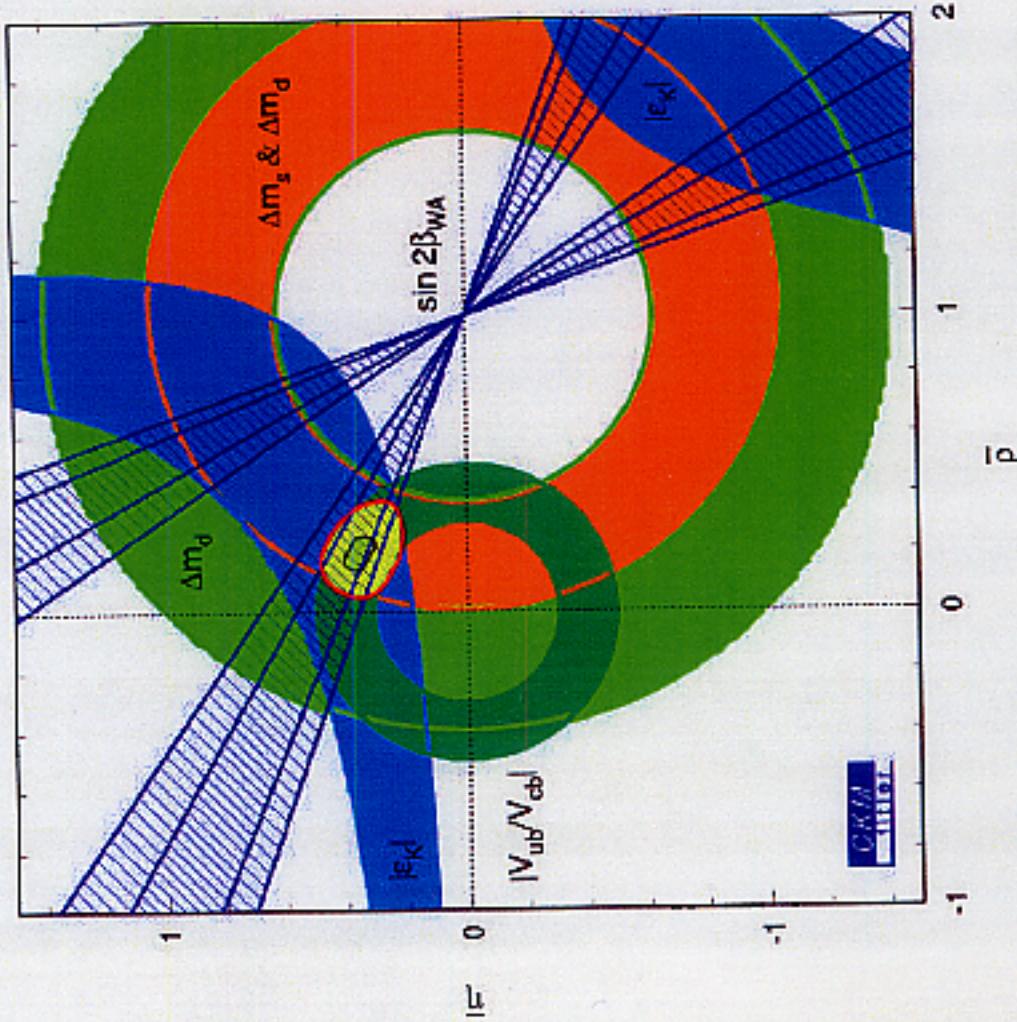


Regions of >5% CL

A. Höcker, H. Lacker, S. Laplace,
F. Le Diberder, Eur. Phys. Jour.
C21 (2001) 225, [hep-ph/0104062]

World Average
 $\sin 2\beta = 0.78 \pm 0.08$

The Standard Model (and the CKM paradigm, in particular) wins again . . . at least at the current level of experimental precision, in this decay mode.



Present data described by SM

$$\mathcal{L}_{\text{Yukawa}} = \sum_{i,j} [\Gamma_{ij}^u \bar{Q}_i \phi^c u_R^j + \Gamma_{ij}^d \bar{Q}_i \phi d_R^j] + \text{c.c.}$$

diagonalization of Γ^u, Γ^d : masses & V_{CKM}

Future data may reveal discrepancies
in measurement of d , rare decays ...

Is there an explanation of Yukawa, i.e.
6 quark masses, 4 mixing angles
 $\times 2$ for lepton sector
below the Planck scale?

We might be lucky!

B physics provides wonderfully
rich field of exploration.

The Higgs sector

SM has efficient mechanism for generating fermion and gauge boson masses

$$\mathcal{L}_{\text{Higgs}} = (D_\mu \phi)^+ (D^\mu \phi) - \underbrace{\lambda (\phi^\dagger \phi - v^2)}_{V(\phi)}$$

Minimum of potential at $\phi = \begin{pmatrix} 0 \\ v \end{pmatrix}$

$$(D_\mu \phi)^+ (D^\mu \phi) \rightarrow \underbrace{\frac{(gv)^2}{2}}_{m_W^2} W_m^+ W^m \left(1 + \sqrt{2} \frac{H}{v}\right)^2 + \dots$$

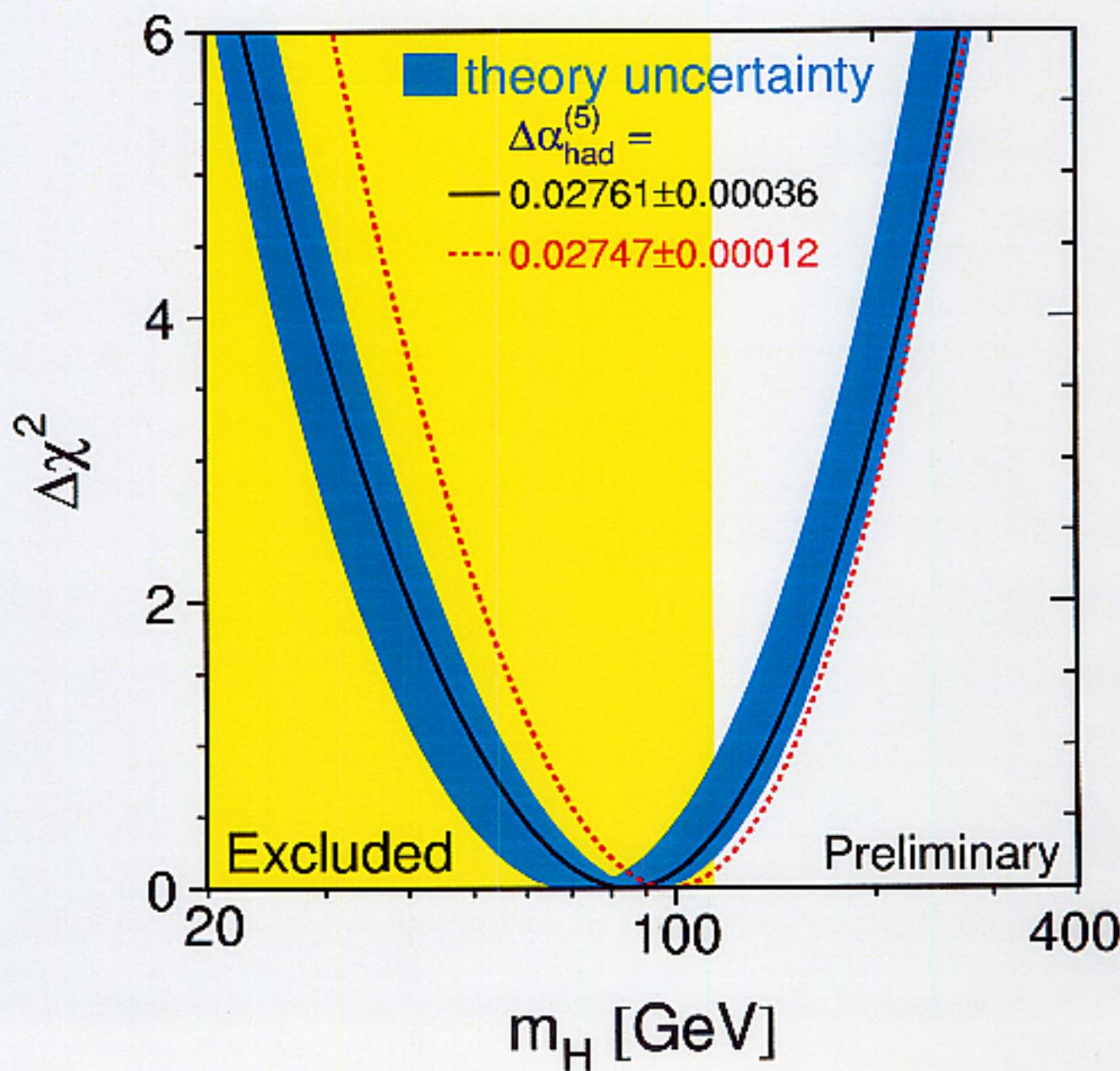
Fermion mass generation from
 $\phi \rightarrow \begin{pmatrix} 0 \\ v \end{pmatrix}$ in Yukawa

- Unconfirmed
- Can be probed at Tevatron, LHC, LC

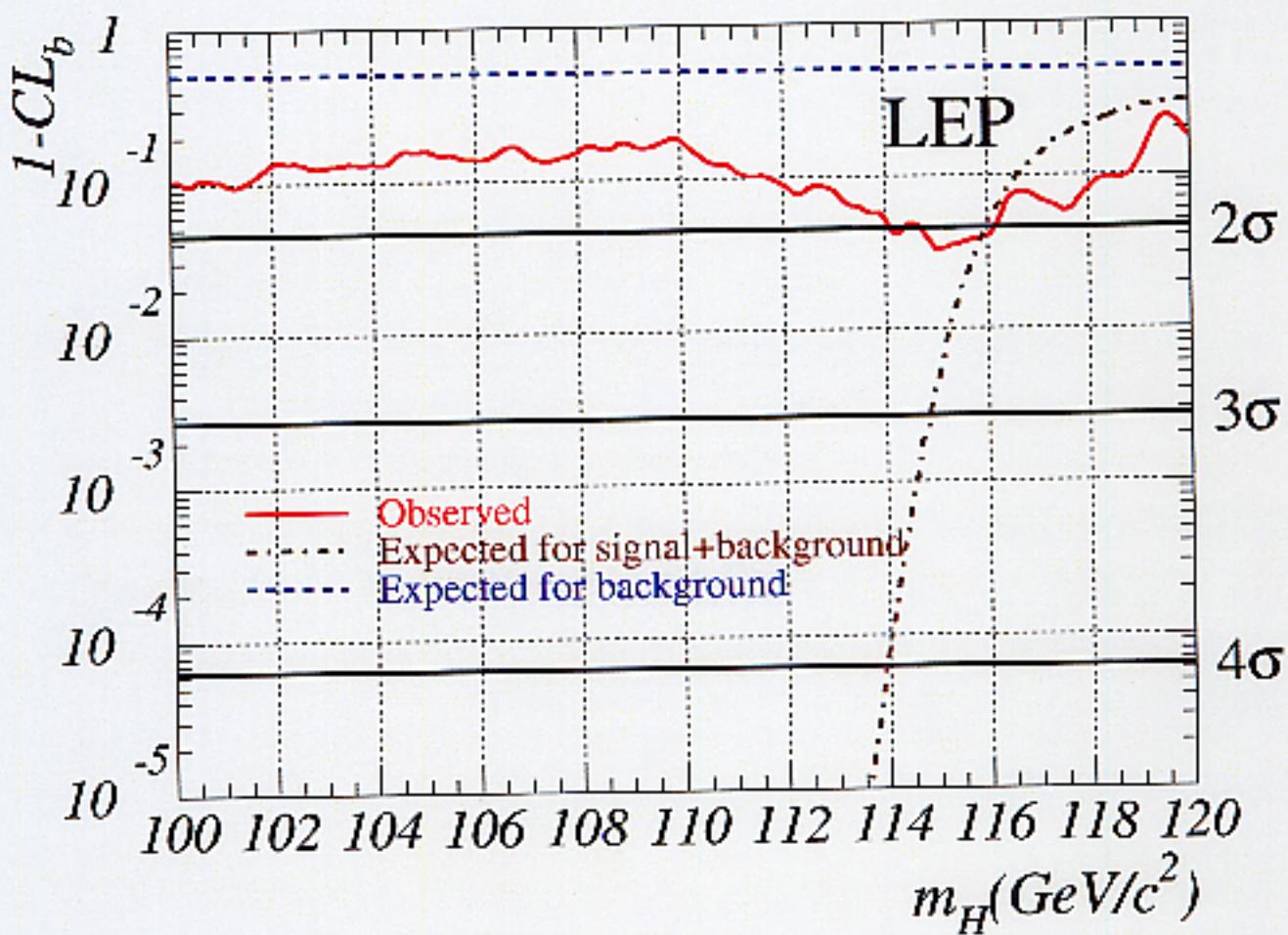
Constraints from EW precision data

$m_H \lesssim 200 \text{ GeV}$ @ 95% CL

Direct search: $m_H > 114 \text{ GeV}$

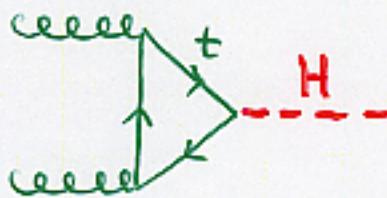


LEP: 2.1σ hint for Higgs at
 $m_H \approx 115.6$ GeV



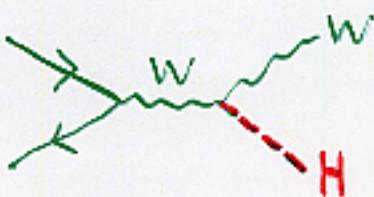
Principal production modes at hadron colliders

gluon fusion



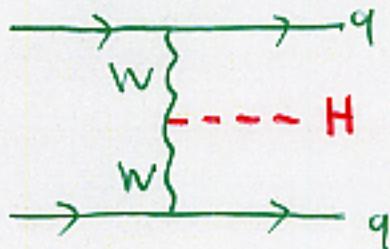
Tevatron LHC

WH/ZH
production



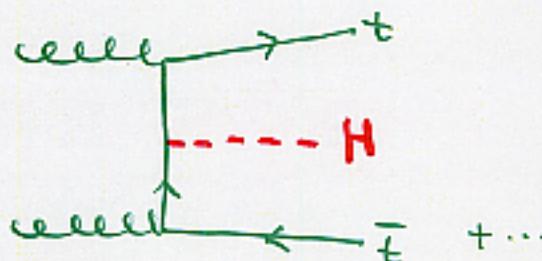
Tevatron

weak boson
fusion



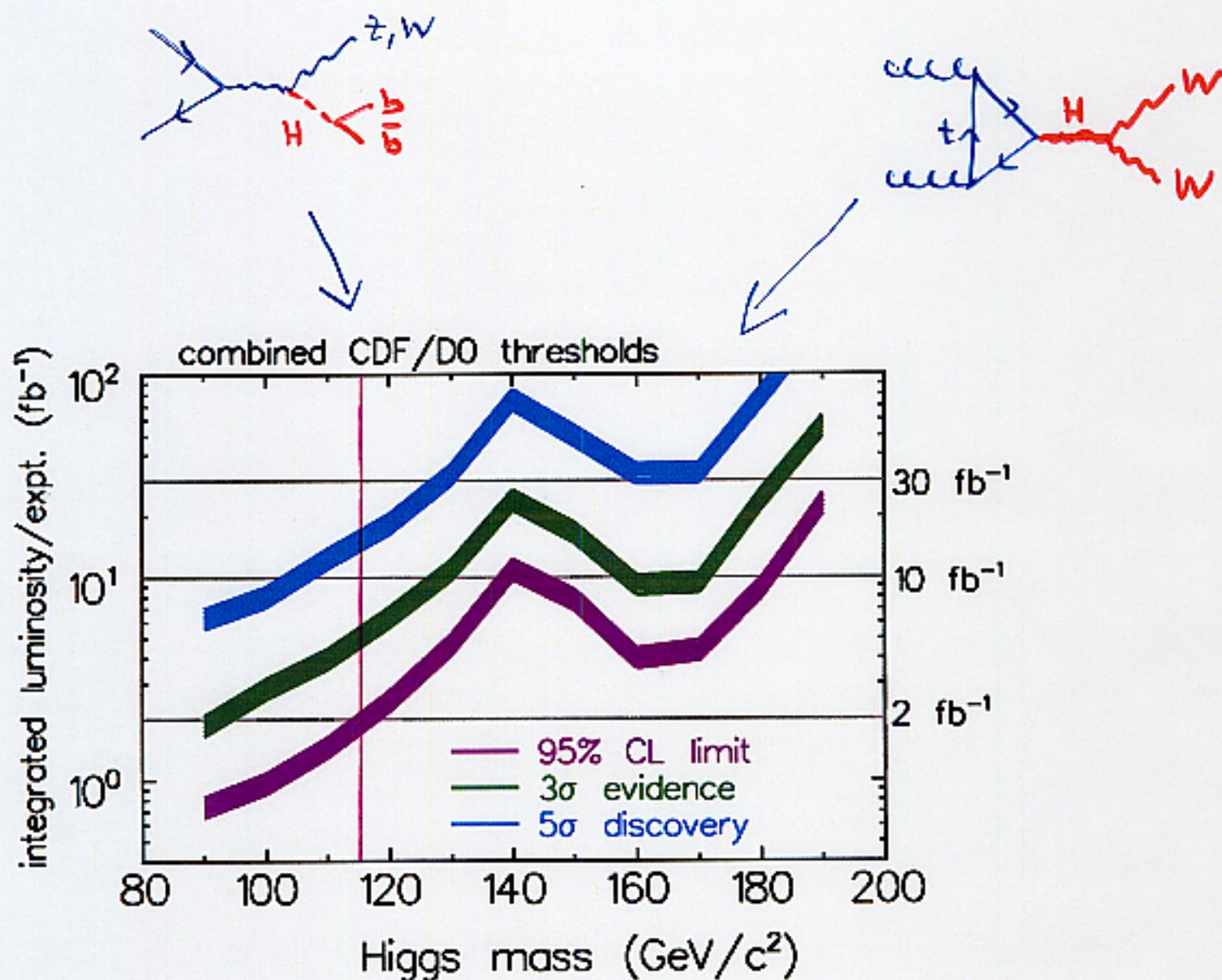
LHC

$t\bar{t}H$ production

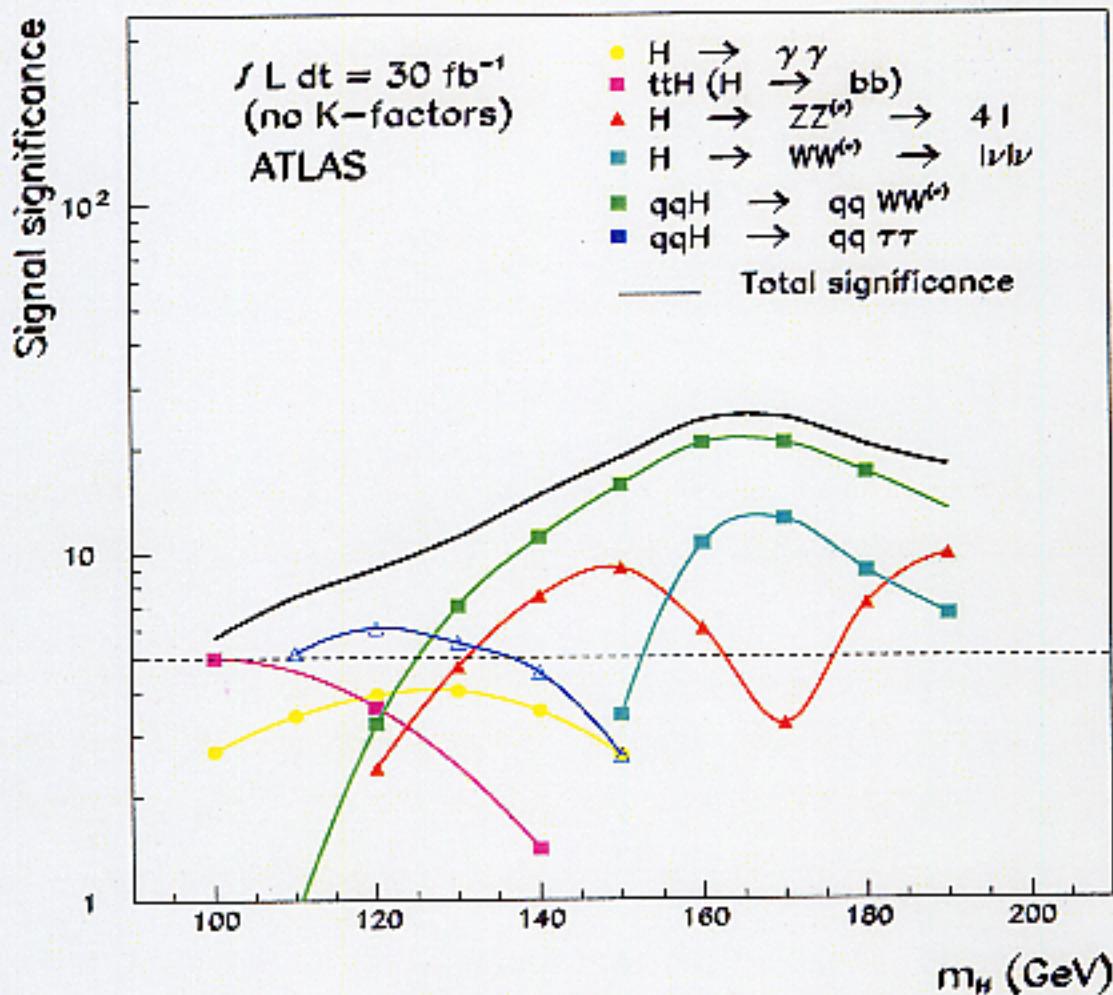


LHC

Expected Tevatron sensitivity



ATLAS Higgs discovery potential for 30 fb⁻¹



- Vector boson fusion channels improve the sensitivity significantly in the low mass region
- Several channels available over the full mass range (important for Higgs boson parameter determination)

Continuous improvement of Higgs search techniques

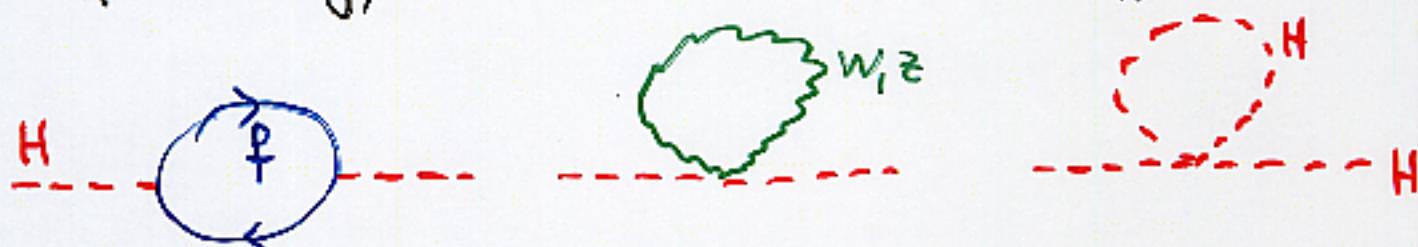
- weak boson fusion at the LHC
- $t\bar{t}H$ channels
- $H \rightarrow \tau\tau$ and $H \rightarrow WW^*$ modes
- multiple channels allow for coupling measurements with hadron collider data
- significant improvements at a linear collider

New physics at the TeV scale?

Naturalness: why is

$$v = 246 \text{ GeV} \ll M_{\text{Planck}} = 10^{19} \text{ GeV}$$

self energy corrections to m_H

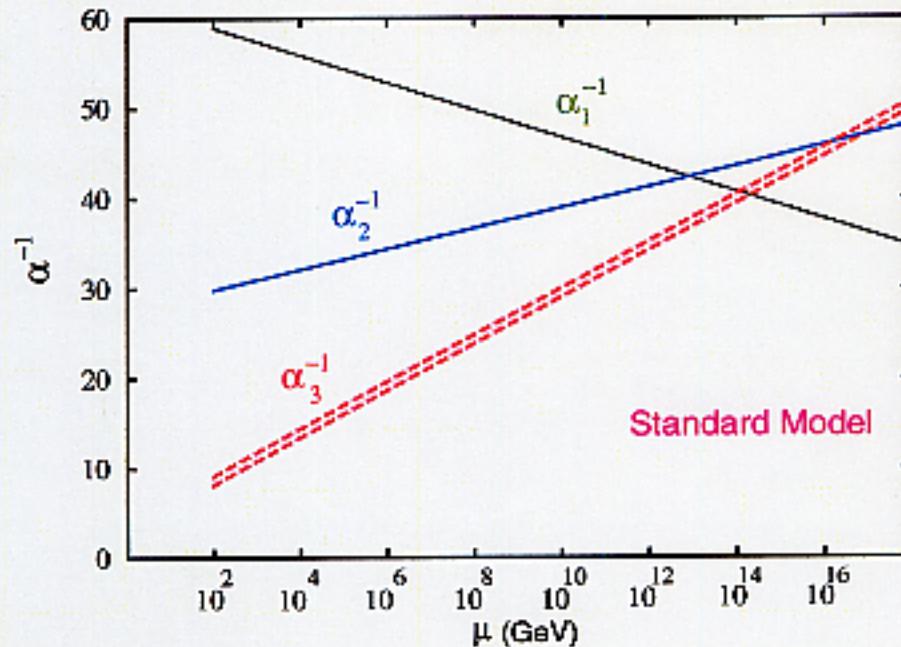


$$\delta m_H^2 \sim \Lambda^2 = \begin{cases} M_{\text{Planck}}^2 & \text{SM} \\ M_{\text{SUSY}}^2 & \text{SUSY} \end{cases}$$

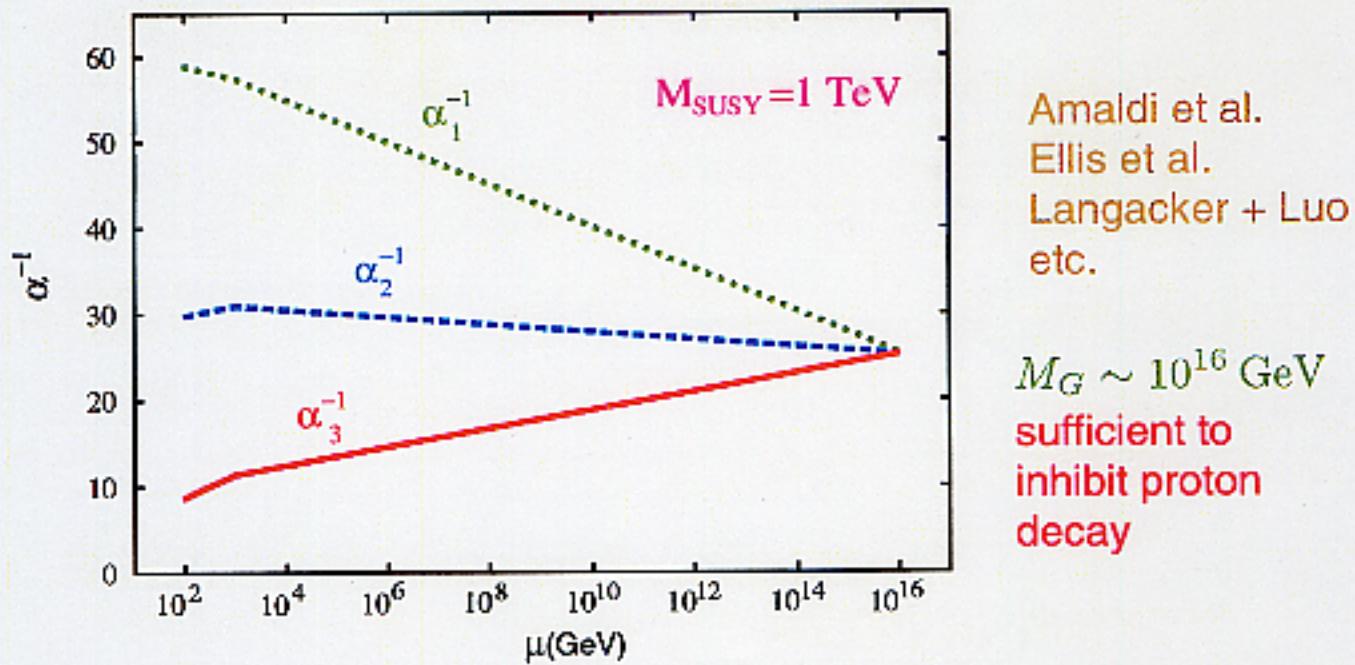
$\Rightarrow M_{\text{SUSY}} = \text{order } 1 \text{ TeV}$ avoids
large radiative Higgs mass shift

Gauge coupling unification
points to the same scale

SM: evolved couplings fail to intersect at common M_X



MSSM: assume common SUSY mass scale $M_{\text{SUSY}} \lesssim 1 \text{ TeV}$
evolved couplings consistent with
common intersection at $M_G \sim 10^{16} \text{ GeV}$



$M_{\text{SUSY}} = 1 \text{ TeV}$ implies production of
squarks, gluinos, charginos... at LHC/Tevatron

Supersymmetry

Fermions \longleftrightarrow Bosons
with identical couplings

Particles

Leptons

quarks

gluon

γ, W, Z

Higgs H_1, H_2

mostly known

Sparticles

sleptons

squarks

gluino

{ charginos

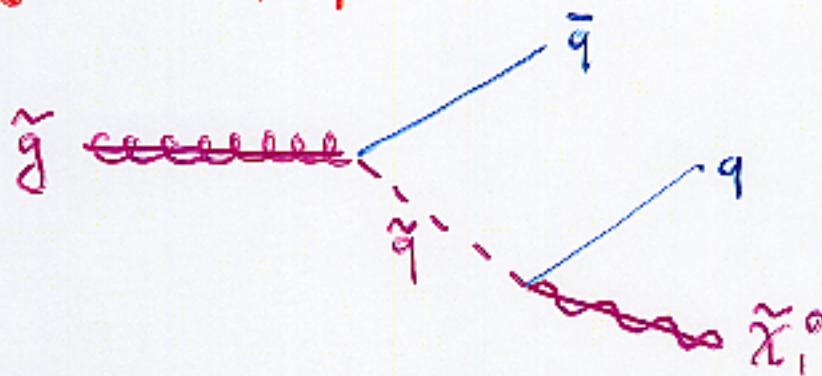
{ neutralinos

none yet found

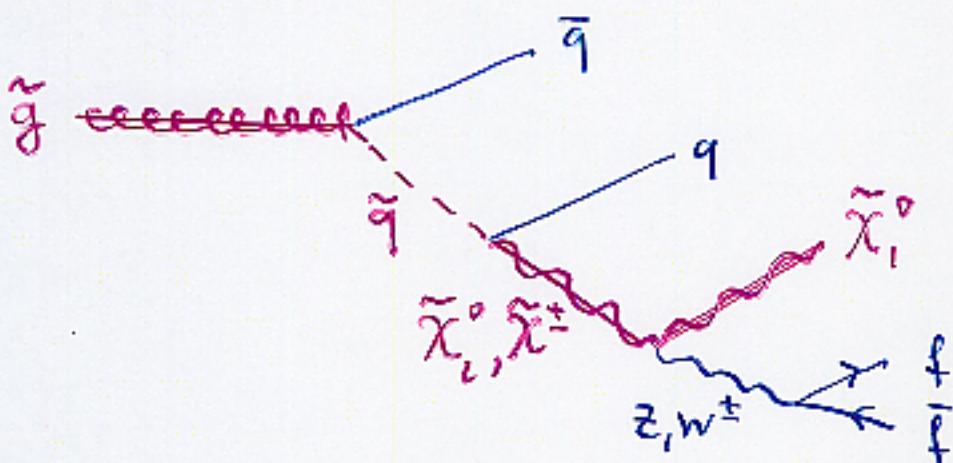
Cosmology: LSP is excellent
dark matter candidate

Signatures at Tevatron and LHC

Jets + \cancel{E}_T



Leptons + jets + \cancel{E}_T



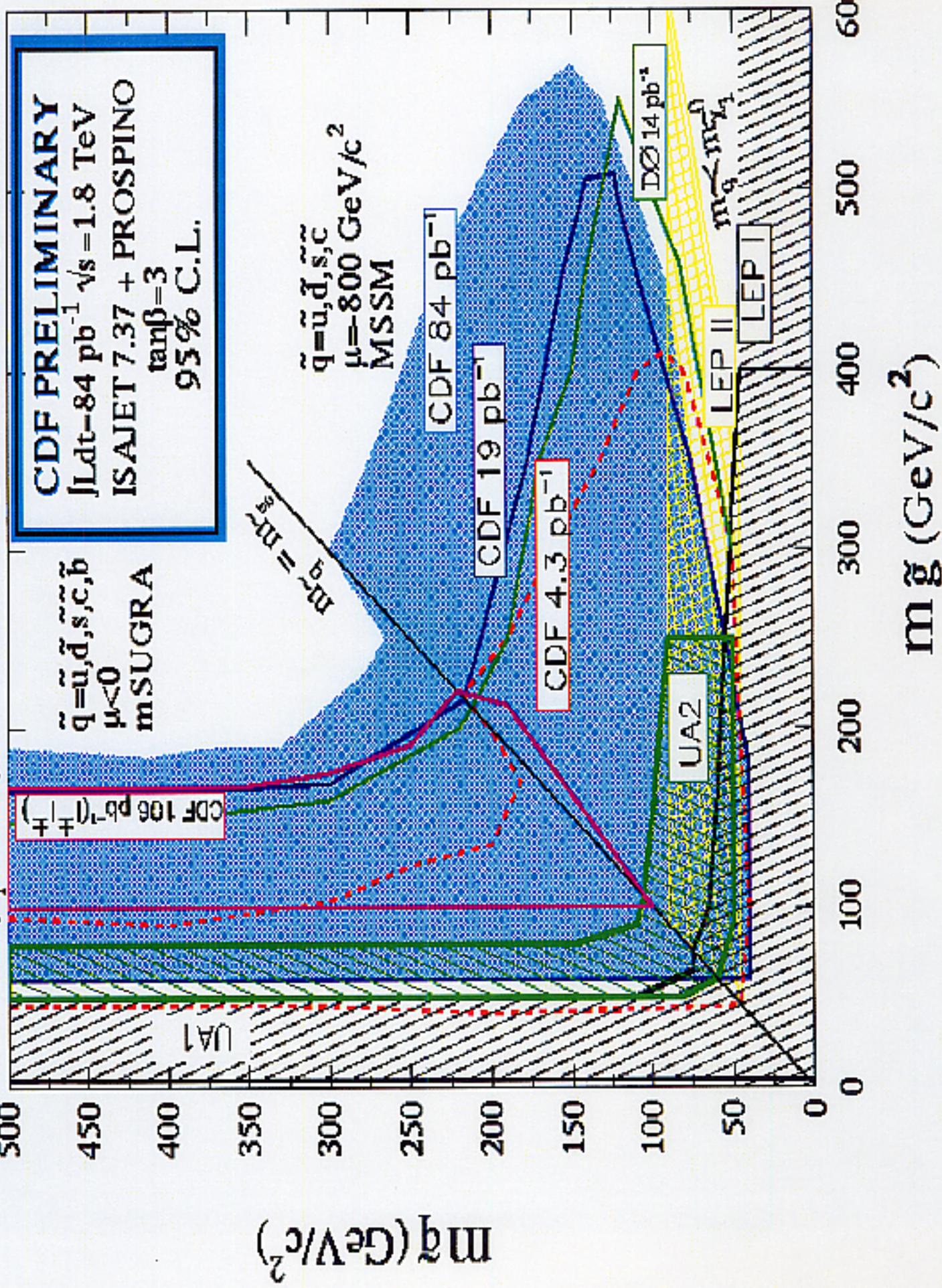
minimal Supergravity (mSUGRA)

stringent unification assumptions

→ sparticle mass relations

LSP = $\tilde{\chi}_1^0$ is stable

$E_T + \geq 3$ jets search for gluinos and squarks



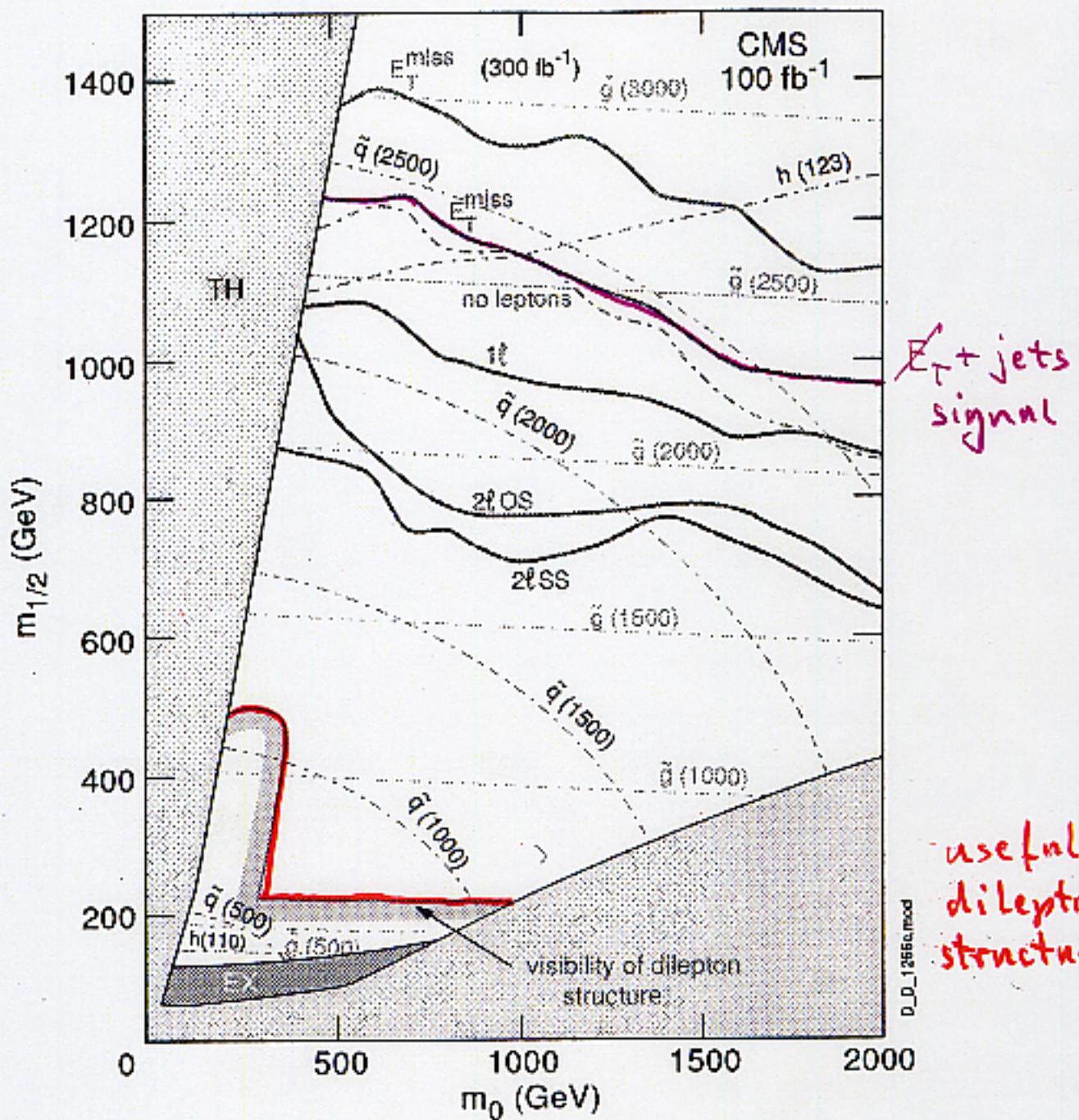


Figure 20: Plot of 5σ reach in minimal SUGRA model for $\tan\beta = 35$ and $\mu = +$ at LHC with 100 fb^{-1} for E_T inclusive, E_T with no leptons, E_T plus one lepton (1ℓ), opposite sign ($2\ell OS$) and same-sign ($2\ell SS$) dileptons, and multi-leptons ($3\ell, 4\ell$). The region where a dilepton edge is visible is indicated. From Ref. [63].

Many other scenarios, in particular for SUSY breaking

- anomaly mediated

- gauge mediated

$$\tilde{\chi}_1^0 \rightarrow \gamma \tilde{G}$$

\Rightarrow displaced photon vertex

R-parity violation, e.g.

$$\tilde{\chi}_1^0 \rightarrow c \bar{d} s \rightarrow 3 \text{jets}$$

We need experimental guidance
= observation of sparticles

Extra dimensions

String theory allows $\delta = 1 \dots 6$ compact extra dimensions of size R :

- SM fields on 3+1 dim. hypersurface
- gravity in 3+1+ δ dimensions

$$F_{\text{gravity}} = G_N^{-1} \frac{m_1 m_2}{r^{2+\delta}} \quad (r < R)$$

Explains why

- gravity weak at large distances
- Newton's constant small

$$G_N^{-1} = 8\pi R^\delta M_D^{2+\delta}$$

Could have

$$R \approx 0.1 \text{ mm} \quad (\text{or smaller})$$

$$M_D \approx 1 \text{ TeV} \quad (\text{or larger})$$

[M_D = scale where gravity becomes strong]

Kalnza-Klein (KK) graviton states
 (torus)

$$x^M = (x_4^M, \vec{y}) \quad \vec{y} \text{ in } 5 \text{ dimensions}$$

$$h^{M\nu}(x) = \sum_{\vec{n}} h_{\vec{n}}^{M\nu}(x_4) e^{i \frac{2\pi \vec{n} \cdot \vec{y}}{R}}$$

$$0 = \square h^{M\nu} = \sum_{\vec{n}} \left(\square_4 - \frac{4\pi^2 n^2}{R^2} \right) h_{\vec{n}}^{M\nu} e^{i \frac{2\pi \vec{n} \cdot \vec{y}}{R}}$$

$\Rightarrow h_{\vec{n}}^{M\nu}$ describes massive graviton

$$\text{mass}^2 = \frac{4\pi^2 n^2}{R^2}$$

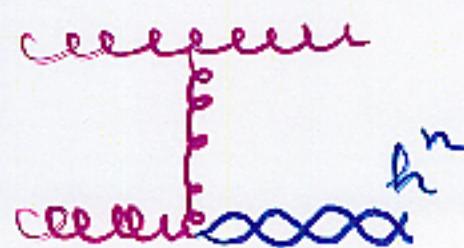
\Rightarrow very many tightly spaced states

$$\text{level spacing} \sim \frac{2\pi}{R} \ll 1 \text{ TeV}$$

Universal coupling to energy-momentum tensor

$$\mathcal{L} = -\sqrt{16\pi G_N} \int d^4x h_{\mu\nu}^{\vec{n}} T^{\mu\nu}$$

\Rightarrow graviton emission in scattering processes



$$h^n \Rightarrow E_T$$

Cross sections for many KK states add up

e.g. $pp \rightarrow j\cancel{E}_T X$

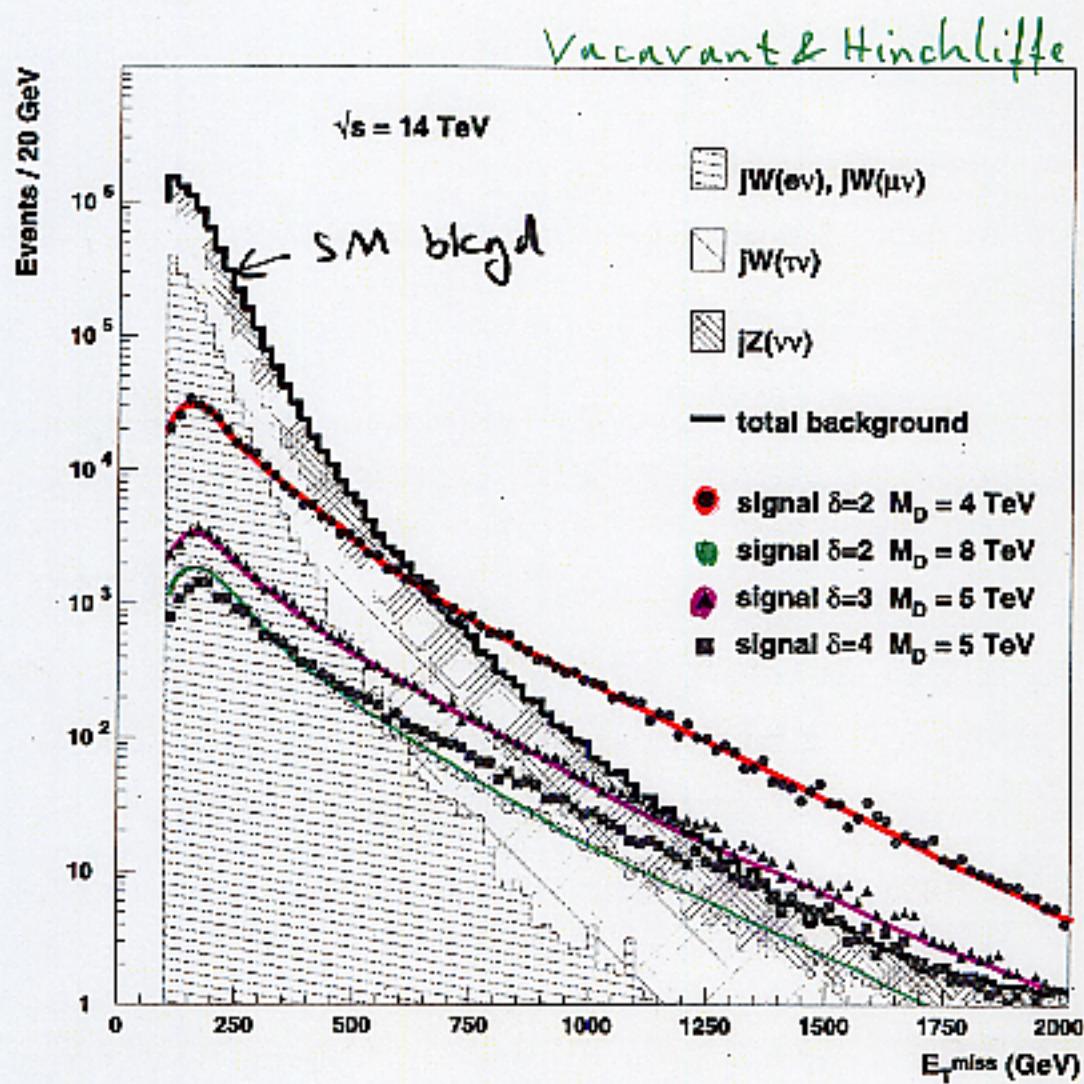


Figure 2. Distribution of the missing transverse energy in background events and in signal events after the selection and for 100 fb^{-1} . The contribution of the three main kinds of background is shown as well as the distribution of the signal for several values of (δ, M_D) .

LHC sensitive to extra dimensions
with $M_D < 9 \text{ TeV} (\delta=2) \dots M_D < 6 \text{ TeV} (\delta=4)$

Many extensions / variants

warped extra dimensions
deconstructed / lattice-ized extra dim.
universal extra dimensions

Rich field for model building

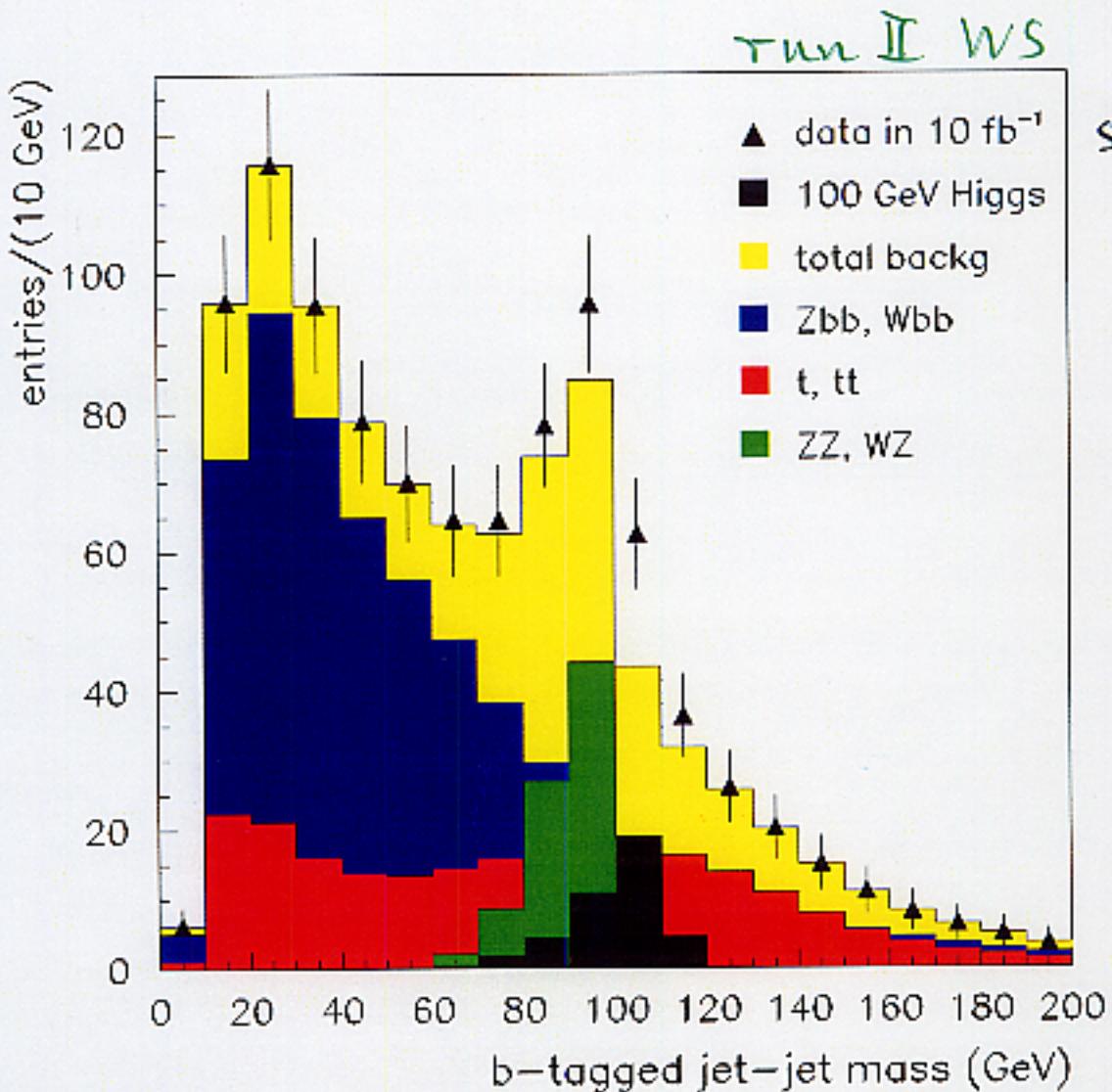
Exciting alternatives for SUSY & technicolor

Badly in need of experimental signatures

Progress at the energy frontier
requires better SM predictions
of collider cross sections for
signals
SM backgrounds

Considerable recent progress
NLO corrections to $2 \rightarrow 3$
NNLO calculations
pdf's with errors
etc.

$q\bar{q} \rightarrow ZH \rightarrow \nu\bar{\nu} b\bar{b}, \ell^+\ell^- b\bar{b}$



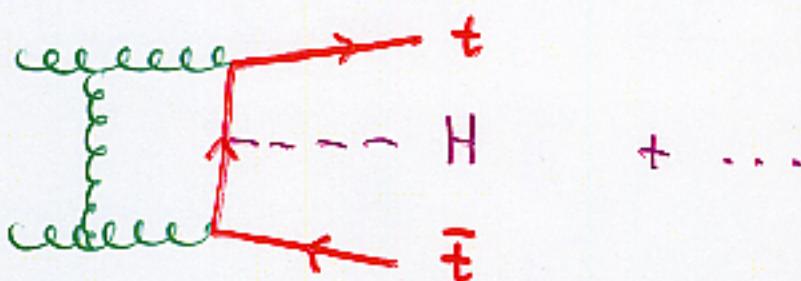
SHW analysis

Need NLO background predictions for
 $Wb\bar{b}$, $Zb\bar{b}$, $t\bar{t}$, ZZ , WZ , Wjj , Zjj

MCFM Monte Carlo

J. Campbell, K. Ellis

$q\bar{q}, gg \rightarrow t\bar{t}H @ NLO$



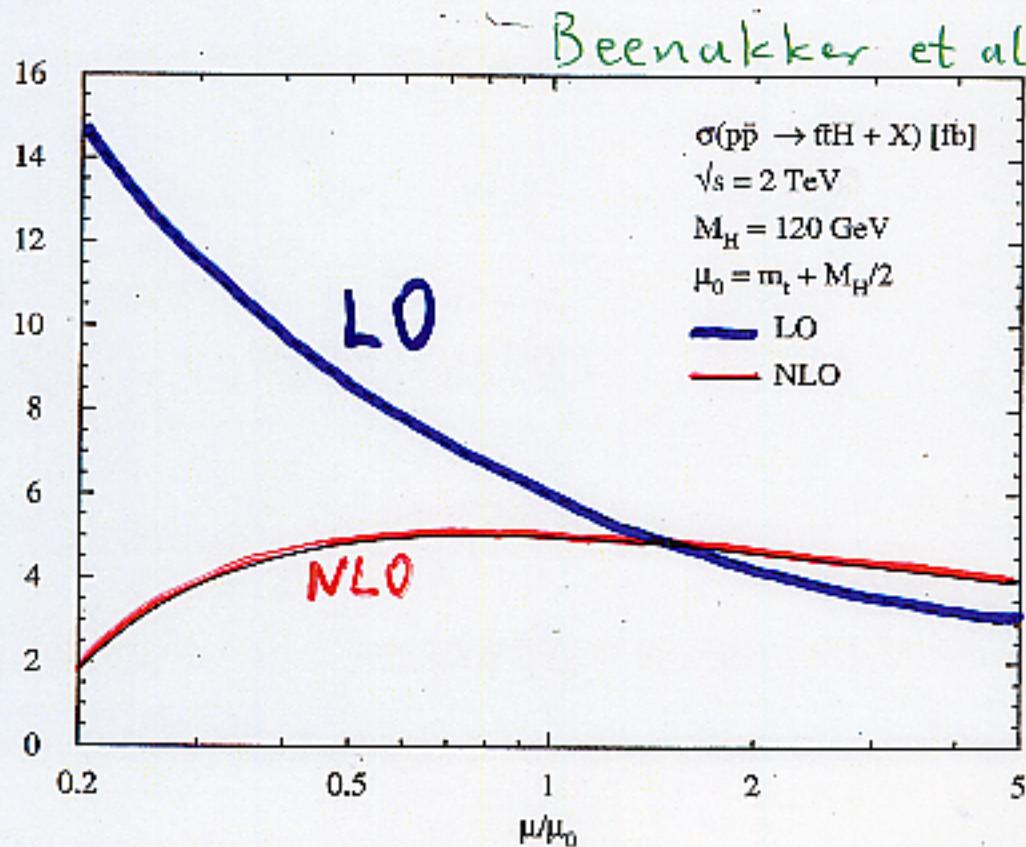
Beenakker, Dittmaier
Krämer, Plümper,
Spira, Zerwas
Reina, Dawson, Walker

Drastic improvement of scale independence

Needed to measure $t\bar{t}H$ coupling

Tevatron : $q\bar{q}$ dominated $\rightarrow K < 1$

LHC : gg dominated $\rightarrow K > 1$



$p\bar{p} \rightarrow jjX$ @ NNLO

2 loop matrix elements calculated

Bern, Dixon, Freitas, Ghinculov

Anastasiou, Glover, Oleari, Tejeda-Yeomans

Next step: assembly into NNLO Monte Carlo

Needed for precise pdf measurement
at the Tevatron

$$\frac{d^3\sigma}{dp_T dy_1 dy_2} \sim f(x_1, \mu) f(x_2, \mu) \frac{d\hat{\sigma}}{d\Delta y}$$

$$x_{1,2} = \frac{p_T}{\sqrt{s}} (e^{\pm y_1} + e^{\pm y_2})$$

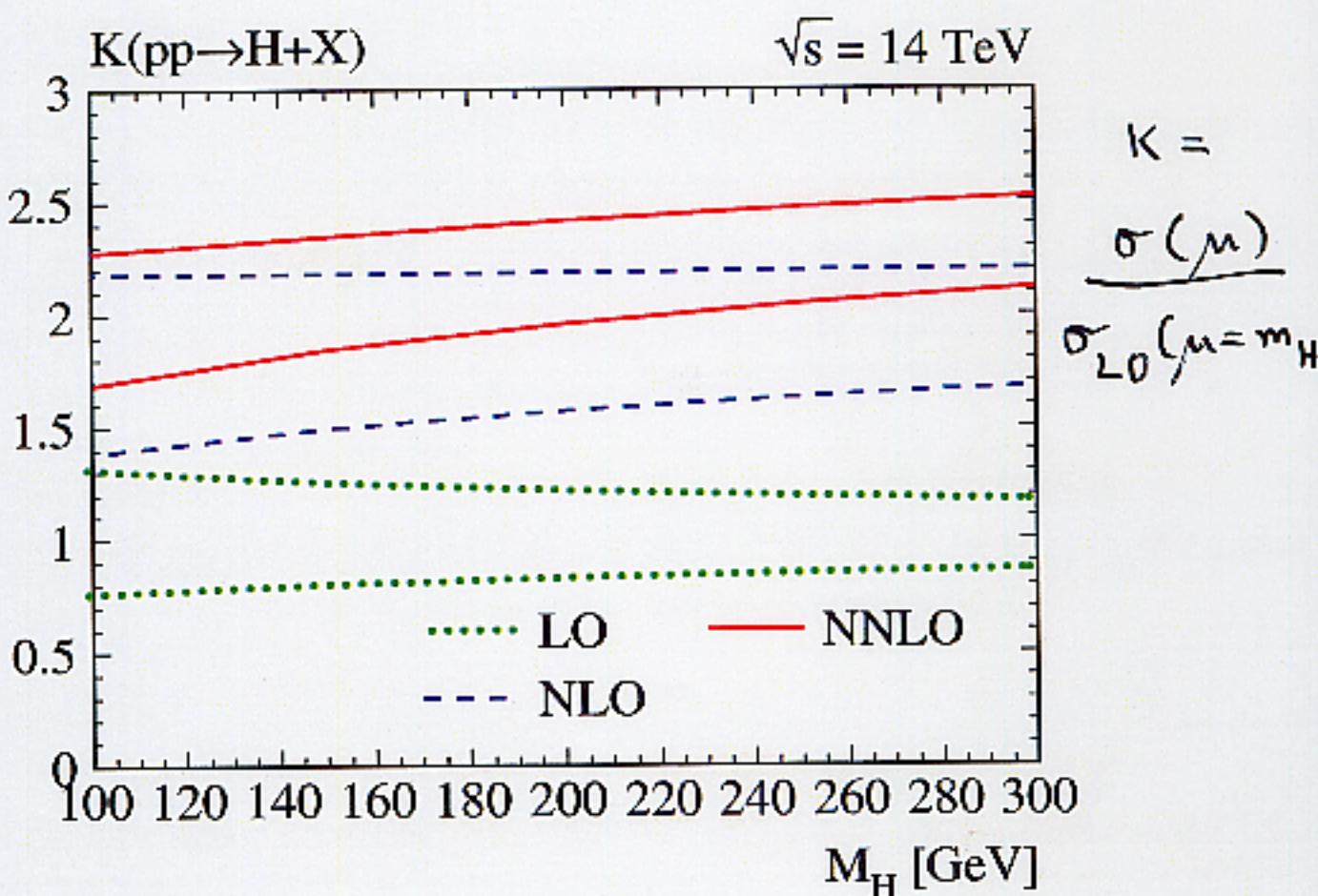
goal: pdf error well below 5%

$gg \rightarrow HX$ at NNLO

[Harlander, Kilgore hep-ph/0201206]

Reduce $\frac{\delta\sigma}{\sigma} < 20\%$.

Crucial for Higgs coupling measurement at LHC

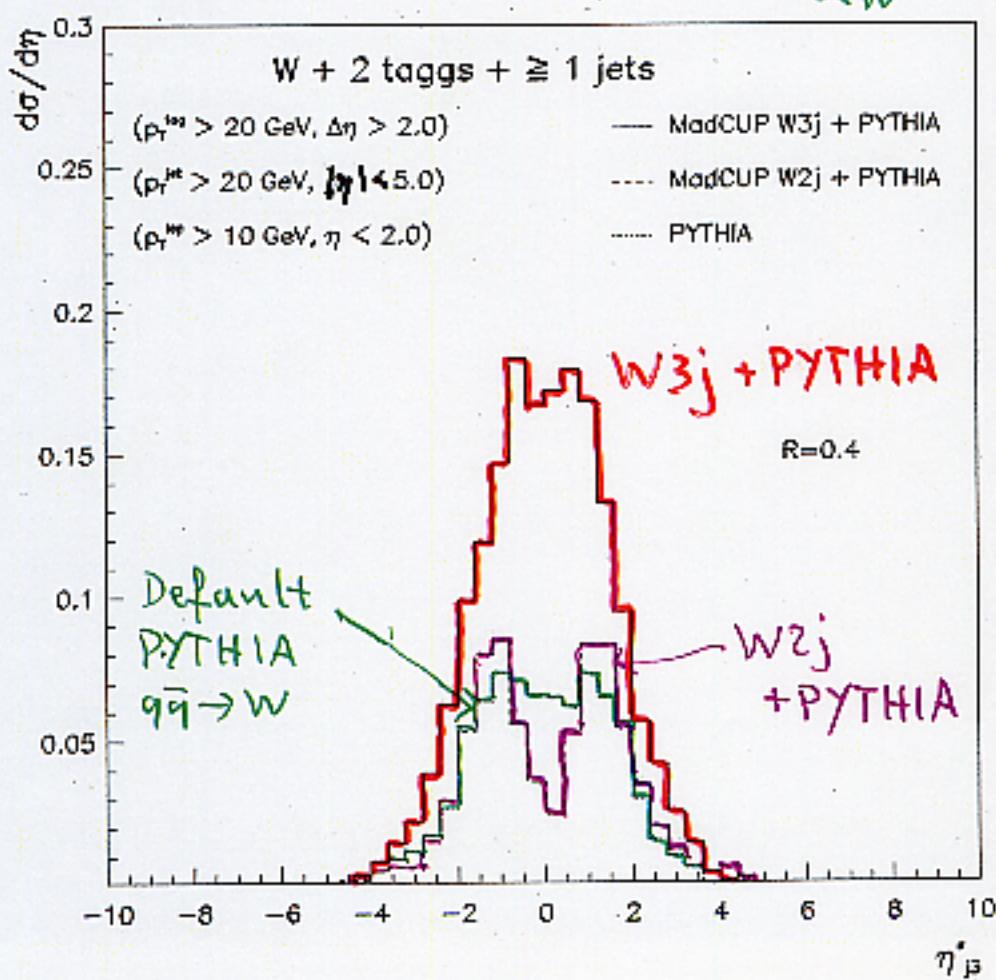


Some open problems are much simpler

$W + 3 \text{ jet}$ at tree level

Now available: full color & flavor information interface for $W+2$ & $W+3$ partons with PYTHIA. Parton shower generates additional jets

$$W2j: \mathcal{O}(d_S^2) \quad \overline{\text{F}}_{WW}^{\text{min}}$$
$$W3j: \mathcal{O}(d_S^3) \quad \overline{\text{F}}_{WW}^{\text{min}}$$



$$\gamma_3^* = \gamma_3 - \frac{\gamma_1 + \gamma_2}{2}$$

$$p_{T1} > p_{T2} > p_{T3} > \dots$$

High energy frontier will be defined by Tevatron & LHC for the foreseeable future.

Reduction of theory uncertainties requires significant investment

- more higher order QCD corrections
- interaction between theory and experiment
- faculty jobs for the young phenomenologists

State of the field in 2002

Golden age of neutrino physics

The B sector reveals its secrets

Fascinating discoveries in cosmology

At threshold of exploring TeV scale
at the Tevatron and the LHC

Particle Physics is vital!